The International VLBI Service for Geodesy and Astrometry and Its Fundamental Role in Earth-related Sciences and Applications

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Abstract. Very Long Baseline Interferometry (VLBI) plays a unique and fundamental role in the maintenance of the global (terrestrial and celestial) reference frames, which are required for precise positioning in many research areas such as the understanding and monitoring of global changes, geodesy, and space missions. The International VLBI Service for Geodesy and Astrometry (IVS) coordinates the global VLBI components and resources on an international basis. The service is tasked by the International Association of Geodesy (IAG) and International Astronomical Union (IAU) to provide products describing the Celestial Reference Frame (CRF) through the positions of quasars, to provide products describing the Terrestrial Reference Frame (TRF), such as station positions and their changes with time, and to generate products describing the rotation of the Earth in space. VLBI uniquely provides the time difference UT1-UTC. This paper summarizes the evolution and current status of the IVS. It points out the activities to improve further on the product quality to meet future service requirements, which will come up with the need for highly precise global reference frames.

Keywords. *International VLBI Service for Geodesy and Astrometry, Very Long Baseline Interferometry (VLBI), Earth Orientation Parameters (EOP), Terrestrial Reference Frame (TRF), Celestial Reference Frame (CRF).*

1. Introduction

The Very Long Baseline Interferometry (VLBI) technique has been employed in geodesy for nearly 40 years. It has contributed significantly to the tremendous progress made in geodesy over these decades by measuring the length of intercontinental baselines with highest accuracy, monitoring Earth rotation at the state of the art, and providing the quasar positions as the best approach to an inertial reference frame. VLBI has been a primary tool for understanding the global phenomena changing the "solid" Earth (e.g., National Aeronautics and Space Administration 2002). Today, VLBI routinely monitors Earth rotation and its variations, as well as crustal motion in order to maintain the global (terrestrial and celestial) reference frames, where the work is coordinated by the International VLBI Service for Geodesy and Astrometry (IVS).

The IVS is an international collaboration of organizations that operate or support VLBI components. The goals are

- to provide a service to support geodetic, geophysical and astrometric research and operational activities;
- to promote research and development activities in all aspects of the geodetic and astrometric VLBI technique;
- to interact with the community of users of VLBI products and to integrate VLBI into a global Earth observing system.

The international collaboration is based on a call for participation that was issued in 1998, in accordance with the IVS Terms of Reference (Schlüter 1999). The IVS was inaugurated in February 1999 and the Directing Board held its first meeting at the Fundamental Station Wettzell, Germany in the same month. Since then, Annual Reports and Meeting Proceedings have been published documenting the status and the progress being made (Vandenberg 1999; Vandenberg and Baver 2000-2004; Behrend and Baver 2005-2006). A wealth of information on the IVS and its activities is available online at http://ivscc.gsfc.nasa.gov.

The IVS is a service of the International Association of Geodesy (IAG), the International Astronomical Union (IAU) and the Federation of Astronomical and Geophysical Data Analysis Services (FAGS). The main task of the IVS is the coordination of the globally distributed VLBI components (see below) in order to guarantee the provision of the products and parameters that realize the Celestial Reference Frame (CRF) and the Terrestrial Reference Frame (TRF) as well as monitor the Earth's angular velocity and rotation axis orientation in both reference frames through the Earth Orientation Parameter (EOP). The EOP enables the transformation between TRF and CRF. VLBI is fundamental and unique for the realization of the CRF through a catalogue of quasar positions.

The IAU tasked IVS to maintain the CRF through a resolution at the IAU General Assembly in Manchester, UK, in August 2000. VLBI contributes strongly to the TRF by the determination of station positions, in particular of baseline lengths between the stations. Due to the long intercontinental baselines, VLBI strongly supports the scale of the TRF. Time-series of station positions give information about their movements (plate motions). As it provides the complete set of EOP and uniquely the UT1-UTC (DUT1) parameter and the CRF, VLBI is a key technique for monitoring the global reference frames, and will play an important role in the realization of the recently established Global Geodetic Observing System (GGOS) of the IAG (Pearlman et al. 2006).

2. Current Status of Geodetic VLBI Coordinated by IVS

Figure 1 shows the distribution of the IVS components. As of the beginning of 2006, the IVS consists of

- 1 Coordinating Center to coordinate the daily and long term activities (Goddard Space Flight Center, Greenbelt, USA).
- 30 Network Stations for the acquisition of VLBI data;
- 3 Operations Centers to coordinate the activities of the Network Stations (Geodetic Institute of the University of Bonn, Germany; Goddard Space Flight Center, Greenbelt, USA; U.S. Naval Observatory, Washington, USA);
- 6 Correlators for processing the acquired data (Max-Planck-Institute for Radioastronomy, Bonn, Germany; MIT Haystack Observatory, Westford, USA; Institute of Applied Astronomy, Saint Petersburg, Russia; National Institute of Information and Communications Technology (NICT), Kashima, Japan; Geographical Survey Institute, Tsukuba, Japan; U.S. Naval Observatory, Washington, USA);

- 6 Data Centers to distribute the products to users, provide storage and archiving functions (Bundesamt für Kartographie und Geodäsie, Germany; Crustal Dynamics Data Information System, USA; Geodetic Data Archive Facility, Italy; National Institute for Astrophysics, Italy; NICT, Japan; Paris Observatory, France);
- 21 Analysis Centers, analyzing the data, processing the results and products;
- 7 Technology Development Centers for developing new VLBI technology;

Figure 1

In total, there are 74 Permanent Components, representing 37 institutions in 17 countries with ~250 Associate Members. IVS coordinates the activities of all VLBI components for geodetic and astrometric use based on their proposals. The contributions are dependent on the individual possibilities of the institutions, meaning that each institution provides as much as its resources allow.

2.1 Coordinating Center

The IVS Coordinating Center (CC) at NASA's Goddard Spacer Flight Center (GSFC) is responsible for the coordination of both the day-to-day and the long-term activities of the IVS, consistent with the directives and policies established by the Directing Board. Primary functions of the CC include the preparation of the master observing plan for each calendar year, the organization of workshops and meetings, the production and publication of reports and communications, and the maintenance of the IVS information system (e.g., website and mailing lists).

2.2 Network Stations

Figure 1 shows the locations of the antenna sites in the 17 countries that support geodetic and astrometric VLBI realized by IVS. One third of the antennas are dedicated to geodetic/astrometric observing, whereas the others are dual use (geodesy and radio astronomy). The IVS aims at increasing the number of network stations in the Southern

Hemisphere. The network stations participate in observing sessions several times a week to several times a year depending on their possibilities. An observing session lasts 24 hours and usually involves 6-8 stations. Some stations carry a high load of observations and are included in most of the observing sessions, while other stations can only contribute to dedicated campaigns.

Stations like Wettzell (Germany) and Kokee Park (USA) are regularly involved in the entire observing program. Other stations, such as O'Higgins or Syowa (Antarctica), contribute only campaign-wise, due to their very remote location. Many stations are operating with aging instrumentation with hardware from the late 1960ies and have increasingly to deal with RFI (radio frequency interference).

A vision for a next-generation VLBI system has been formulated (Niell et al. 2006) and steps are underway to make the new system reality (see Section 5). The various data recording techniques, such as Mark IV and Mark 5 (developed at Haystack Observatory, USA), K4 and K5 (developed at NICT, Kashima, Japan), and S2 (developed in Canada), lead to additional constraints for the combination of network stations in common observing sessions, because the correlators are dedicated to one recording system only. The development of the VLBI Standard Interface (VSI) will help to overcome such limitations in the future.

Most of the antennas are not primarily designed for geodetic and astrometric VLBI. Deformations of the telescope structures will lead to variations of the reference point, which is usually assumed as an invariant point of the telescope. Systematic errors due to such deformations will have to be considered. The raw data are recorded onto transportable disk systems and then shipped to the correlators. The storage requirement for a typical 24-hour observing session amounts to around 1 TB. The transportation of the data to the correlator is one of the major reasons for the time delay of the products. Access to high-speed data links for data transfer is currently becoming available at many stations. Due to the remoteness of VLBI antennas, the last-mile problem (connection of the antenna site to the backbone of a high-speed network) poses a difficulty and introduces an additional cost. Time and frequency information is provided by H-masers for precise frequency generation and by employing GPS time-transfer receivers to compare the local timescale to a global time scale, such as UTC(GPS). The current stability of the H-masers supports the accuracy of the observable to 20 to 30 ps; the comparison via GPS is good to approximately 100 ns.

2.3 Operation Centers and Correlators

There are three Operation Centers, which coordinate the routine operations of the network stations and prepare the detailed observation schedules. The schedules are posted to a Data Center with sufficient lead time (a week or more) before the start of a session. Most of the observing sessions are correlated with the Mark IV/Mark 5 correlators at the U.S. Naval Observatory (Washington, USA), the Max-Planck-Institute for Radioastronomy (Bonn, Germany), and Haystack Observatory (Westford, USA). Some experiments are correlated with the K4/K5 correlators in Kashima and Tsukuba, Japan, and some with the S2 correlator in Penticton, Canada. A big step forward was made by the development of the disk-based recording systems Mark 5 and K5. The VLBI Standard Interface (VSI) will make it possible to overcome the different data formats and recording philosophies.

The Mark 5 correlators have the capability to correlate up to 16 stations in a single pass depending on the number of available playback units. Sessions with more stations than playback units are correlated in multiple passes. Since access to high-speed data links has not been realized routinely, the time delay from observation to product delivery is dominated by the shipment of the disk media. For the two weekly rapid-turnaround sessions, the time delay for product delivery is about 10 days on average. Other session types have delays from several weeks up to a month. High-speed links at Haystack Observatory have enabled routine e-transfer of observation data from Tsukuba and Kashima, both Japan, and further stations will follow soon. First experiences are being gathered with a software correlator at the Geographical Survey Institute (GSI) in Tsukuba, Japan, for the baseline Wettzell–Tsukuba. Software correlators, which use general-purpose computers (e.g., commodity PCs) instead of custom-built electronic hardware, are likely to become important for providing products in real time.

2.4 Data and Analysis Centers

Six Analysis Centers (ACs) do the regular product submission to the Data Centers, employing software programs such as CALC/SOLVE (Ma et al. 1990), OCCAM (Titov et al.

2004) and SteelBreeze (Bolotin 2000). Associate Analysis Centers regularly submit specialized products, such as tropospheric and ionospheric parameters, using complete series or subsets of VLBI observing sessions and perform special investigations and research. The results derived from the same dataset obtained by different ACs show biases of the order of the internal precision (about 10 ps in delay). Studies to reduce the differences are under way.

The results of six ACs are combined to obtain the official IVS solutions. To improve the product reliability more ACs and more software packages need to be involved in the procedure. The routine analysis process requires more automation for near-real time provision of products. The six Data Centers are repositories for VLBI observing schedules, station log files, and data products. The three primary Data Centers mirror each other to make the distribution and maintenance of data and products more efficient and reliable.

2.5 Technology Developing Centers

Technology developments for IVS are mainly carried out by the Haystack Observatory and by NICT in collaboration with related groups. The development of digital data recorders, the developments in e-VLBI (electronic VLBI using high-speed networks), and the progress in the VLBI Standard Interface (VSI) should be noted as significant steps forward in the last two years. VSI provides a standardized specification for VLBI data formats and protocols that is compatible between both homogeneous and heterogeneous VLBI data systems (Whitney 2006). These developments will play a key role in the evolution of the IVS as it will allow full interoperability between various VLBI systems while allowing separate development avenues.

3. Current and Future Products

When IVS started in early 1999, the continuity requirement for maintaining the terrestrial and celestial reference frames forced the continuation of the existing observing programs set up by the U.S. Naval Observatory for the National Earth Orientation Service (NEOS), or by NASA for the Continuous Observations of the Rotation of the Earth (CORE). In 2001, a working group (WG2) was established to review the products and the existing observing programs. The WG2 report (Schuh et al. 2002) was the basis for improving products and evolving observing programs to meet service requirements.

The IVS products can be defined in terms of their accuracy, reliability, frequency of observing sessions, temporal resolution of the estimated parameters, time delay from observing to final product, and frequency of solutions. The situation before 2002 and the goals for the follow-on years with IVS products are described in detail in the WG2 report (Schuh et al. 2002). The main IVS products, their current accuracies and the goals are summarized in Table 1. The VLBI technique allows us to provide additional products and IVS intends to set up the extended products summarized in Table 2.

Table 1

Table 2

Until the end of 2001, IVS products were generated from ~3 days/week observing with six-station networks. The time delay from observing to product delivery ranged from one week up to four months, with an overall average value of 60 days. From 2002 to date, many of the goals outlined in the WG2 report have been achieved:

- all products are delivered on a regular, timely schedule,
- the accuracies of all EOP and TRF products have improved by a factor of 2 to 4,
- the average time delay has decreased from 60 to 30 days, and two days per week rapid turnaround sessions (IVS-R1 and IVS-R4) are observed with an average time delay of 10 days.

The more ambitious goals are still being worked on:

- increase the frequency of observing sessions from ~3 to ~7 days per week,
- improve the sky distribution of the CRF,
- reduce the time delay to 3 to 4 days, and eventually to 1 day.

4. Current Observing Program

4.1 Overview of Observing Sessions

To meet its product goals, beginning with the 2002 observing year and continuing until today, IVS designed an observing program coordinated with the international community. Since 2002, the observing program has included the following sessions:

- EOP: Two rapid turnaround sessions each week (IVS-R1 and IVS-R4), initially with 6 stations, increasing to 7-8. These networks were designed with the goal of having comparable polar motion results (x_p and y_p). One-baseline, 1-hr Intensive sessions four times per week, increasing to seven times per week in 2004.
- TRF: Monthly TRF sessions with 8 stations including a core network of 4 to 5 stations and using all other stations three to four times per year. In mid 2005, changing to 16 stations observed six times per year.
- CRF: Every three to four weeks, dedicated CRF sessions to provide astrometric observations that are useful in improving the current CRF and in extending the CRF by observing "new" sources. Bi-monthly RDV (R&D with the VLBA) sessions using the 10 stations of the Very Long Baseline Array (VLBA) and 10 geodetic stations, providing state-of-the-art astrometry as well as information for mapping CRF sources.
- Monthly R&D sessions to investigate instrumental effects, research the network offset problem, and study ways for technique and product improvement.
- Bi-annual, if resources are available, 14-day continuous sessions (like the CONT02 and CONT05 campaigns) to demonstrate the best results that VLBI can offer, aiming for the highest sustained accuracy.

Although certain sessions have primary goals, such as CRF, all sessions are scheduled so that they simultaneously contribute to all geodetic and astrometric products. The observing program and product delivery was accomplished by making some changes and improvements in IVS observing program resources (station days, correlator time, and storage media), by improving and strengthening analysis procedures, and by a vigorous technology development program.

4.2 Experiences with the Observing Program

The number of station observing days increased by about 10% in 2002 compared to 2001, with an additional 12% devoted to the CONT02 campaign. Not counting CONT02, the number of observing days increased by another 12% in 2003, in 2004 and also in 2005. In 2005 the CONT05 was performed (MacMillan et al. 2006), in order to provide the best data set VLBI ever had. The International GNSS Service (IGS) and the International Laser Ranging Service (ILRS) enhanced their observation during the campaign, which promised best results in the combination of the techniques.

The required observing days will continuously increase such that by 2007 the top 12 geodetic stations will need to observe up to 4 days per week—an ambitious goal. Increased station reliability and unattended operations can improve temporal coverage by VLBI and also allow substantial savings in operating costs. Higher data-rate sessions can yield more accurate results, and therefore nearly all geodetic stations have been upgraded to Mark 5 or K5 technology; by the end of 2006 all stations will have upgraded.

As of the end of 2003, the correlators and most of the observing stations were equipped with Mark 5 digital recording systems. All correlators were committed to handling the IVS data processing with priority for meeting timely product delivery requirements. High-capacity disks (120 GB to 250 GB) were purchased and organized in a common pool to replace magnetic tapes and to obtain additional recording media capacity.

The progress in communication technologies supported the breakthrough for e-VLBI. Some stations are already connected to fast Internet links (1 Gbit/s) and regular applications for e-VLBI (real-time or near-real-time) have been established. The 1-hr Intensive observation sessions are routinely transferred electronically to a Mark IV/5 or K5 correlator. The increased amount of VLBI data to be produced under the new observing program required Analysis Centers to handle a larger load. Partially automated analysis procedures help to improve the timeliness of product delivery.

As an official IVS product a complete set of EOPs is regularly submitted to the International Earth Rotation and Reference Systems Service (IERS). The set is obtained as a combination of the individual solutions of six IVS Analysis Centers (Nothnagel and Steinforth 2002).

Until the end of 2001, the parameters were derived from the NEOS observations, while since January 2002 the IVS-R1 and IVS-R4 have been used implementing the WG2 recommendations. The objective of the rapid turnaround observation sessions is to minimize the delay between the observations and the availability of the results. The delay between the observations and the results is better than two weeks since April 2002 (see Table 1). This should be regarded as significant and real progress, even though the WG2 goal of only 4 days has not been achieved.

Improvements for data transmission and a higher throughput at the correlators were achieved, following the implementation of the newly developed Mark 5 digital data recording system, which has e-VLBI capabilities, permitting data transmission via high-speed Internet links. The determination of DUT1 from the now daily 1-hour observations known as “Intensives” have been carried out from 1983 to 1994 on the baseline Wettzell–Westford, from 1994 to 2000 on the baseline Wettzell–Greenbank and since 2000 on the baseline Wettzell–Kokee Park. These weekday Intensives now employ the Mark 5 recording system. In 2002, a time-series on the baseline Wettzell–Tsukuba has been started. These weekend Intensives use the Japanese K5 system. The regular application of fast Internet links for the Intensives facilitates the rapid provision of DUT1, which is now accomplished in three to four days.

The VLBI observations from the IVS-R1 and IVS-R4 allow the determination of tropospheric parameters, in particular the wet zenith path delay. Since July 2003 the zenith wet path delay is an official IVS product. The Vienna University of Technology is combining the solutions of up to nine Analysis Centers to produce total and wet zenith path delays from the weekly rapid turnaround sessions IVS-R1 and IVS-R4 (Schuh et al. 2004).

5. The Future VLBI System

A strategic paper “VLBI2010” for geodetic VLBI has been released in September 2005 for the coordination of developments in the next years, possibly decades (Niell et al. 2006). The IVS Working Group 3 (WG3) was tasked to examine current and future requirements for geodetic VLBI, including all components from antennas to analysis, and to create recommendations for a new generation of VLBI systems. The proposals are based on the recommendations for future IVS products detailed in the IVS Working Group 2 Report (Schuh et al. 2002), on the requirements of IAG's GGOS (Pearlman et al. 2006), and on the science-driven geodetic goals outlined in the NASA Solid Earth Science Working Group Report (National Aeronautics and Space Administration 2002).

The criteria are:

- 1 mm measurement accuracy on global baselines
- continuous measurements for time-series of station positions and EOP
- turnaround time to initial geodetic results of less than 24 hours.

The WG3 sought approaches for the design of the new system that would enable the following performance-enhancing strategies:

- Reduce the random component of the delay-observable error, i.e., the per-observation measurement error, the stochastic properties of the clocks, and the unmodeled variation in the atmosphere
- Reduce systematic errors
- Increase the number of antennas and improve their geographic distribution
- Reduce susceptibility to external radio-frequency interference
- Increase observation density, i.e. the number of observations per unit time
- Develop new observing strategies

All of the above considerations, along with the need for low-cost of construction and operation, required a complete examination of all aspects of geodetic VLBI, including equipment, processes, and observational strategies.

The results of this examination have led WG3 to make the following recommendations:

- *Design a new observing system based on small antennas.* The new system will be automated and operate unattended and will be based on small (10-12 m diameter), fast-moving, mechanically reliable antennas that can be replicated economically. The observing should be done over a broad, continuous frequency range, perhaps 1-14 GHz, which includes both the current S-band and X-band frequencies for backwards compatibility, but allows much more agility to avoid RFI and more bandwidth to significantly improve delay measurement precision. At the same time, the best of the existing large antennas will be updated for compatibility with the new small-antenna system; this will allow them to co-observe with the small-antenna systems to preserve continuity with the historical record, as well as to improve the CRF measurements made primarily by the large antennas.

- *Transfer data with a combination of high-speed networks and high data-rate disk systems.* Data recording rates and transmission rates are rapidly increasing courtesy of vast investments by the computer and communications industries.
- *Examine the possibilities for new correlator systems* to handle the anticipated higher data rates, including correlation based on commodity PC platforms, possibly widely distributed.
- *Automate and streamline the complete data-analysis pipeline,* enabling rapid turnaround and consistent TRF, CRF, and EOP solutions.

The WG3 report identifies specific steps that need to be taken next in order to develop, deploy, and bring the new system into operation. The next steps include two broad categories of efforts:

- *System studies and simulations:* error budget development, decisions on observing frequencies, optimal distribution of new sites, number of antennas per site, new observing strategies, and a transition plan.
- *Development projects and prototyping:* small antenna system, feed and receiver, cost and schedule, higher data rate system, correlator development, backend development, and data management and analysis software.

Results of these studies and projects should be well communicated within the community. The IVS Directing Board established the VLBI2010 Committee (V2C), which is tasked to coordinate the required steps. In addition to the regular meetings of the V2C, the progress of the VLBI2010 efforts is discussed at general VLBI meetings, dedicated workshops and online fora. It is our belief that the envisioned new VLBI system will renew the interest of current funding resources and inspire new interest from universities, industry, and government, based on the exciting possibilities for a more accurate and data-rich geodetic VLBI system.

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Table 1: Summary of current IVS main products: status and goal specifications.

Products	Specification	Status 2002	Status 2006	Goals (2010)
Polar Motion x_p, y_p	accuracy product delivery resolution frequency of solution	x_p ~ 100 µas, y_p ~200 µas weeks – 4 months 1 day 3 days/week	x_p , y_p: 50 – 80 µas 8 – 12 days 1 day	25 µas 1 day 10 min – 1 h 7 days/week
UT1-UTC (DUT1)	accuracy product delivery resolution	5 – 20 µs 1 week 1 day	3 µs 3 – 4 days 1 day	2 µs 1 day 10 min
Celestial Pole $\delta\varepsilon$; $\delta\psi$	accuracy product delivery resolution frequency of solution	100 – 400 µas weeks – 4 months 1 day ~ 3 days/week	50 µas 8 – 12 days 1 day	25 µas 1 day 7 days/week
TRF (x, y, z)	accuracy	5 – 20 mm	5 mm	2 mm
CRF (α; δ)	accuracy frequency of solution product delivery	0.25 – 3 mas 1 year 3 – 6 months	0.25 mas (for more frequency bands) 1 year 3 months	0.25 mas (for more frequency bands) 1 month

Table 2: Overview of future IVS products. (*A Pilot Project to provide baseline length information over time is underway. **Total and wet zenith delays are provided on an operational basis for the R1 and R4 sessions.)

Earth Orientation Parameter additions	• dUT1/dt (length of day) • dx_p /dt; dy_p /dt (pole rates)
Terrestrial Reference Frame (TRF)	• x- , y- , z – time series* • Episodic events • Annual solutions • Non linear changes
Celestial Reference Frame (CRF)	• Source structure • Flux density
Geodynamical Parameter	• Solid Earth tides (Love numbers *h*, *l*) • Ocean loading (amplitudes and phases A_i, f_i) • Atmospheric loading (site-dependent coefficients)
Physical Parameter	• Tropospheric parameters** • Ionospheric parameters • Light deflection parameter

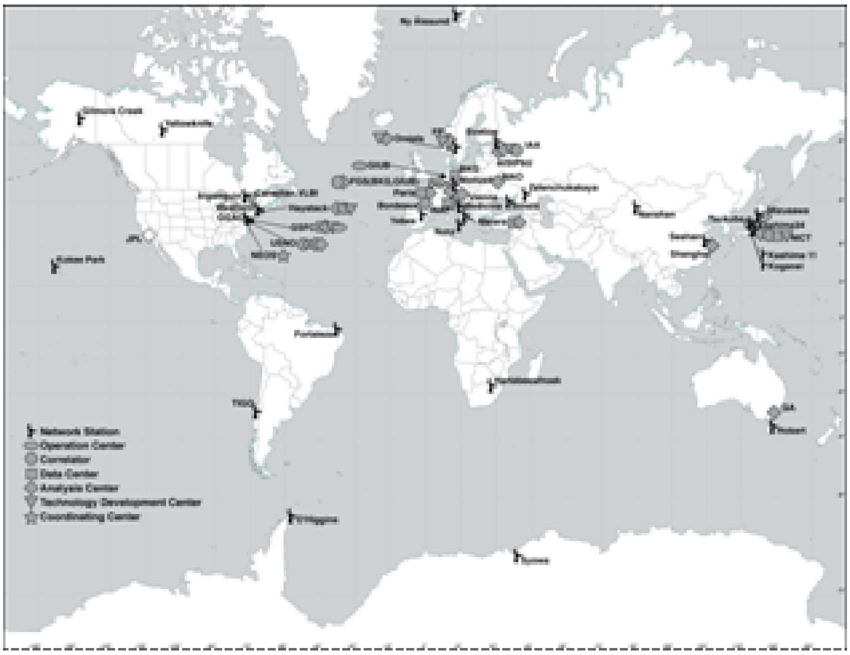

Fig. 1. Global distribution of IVS components